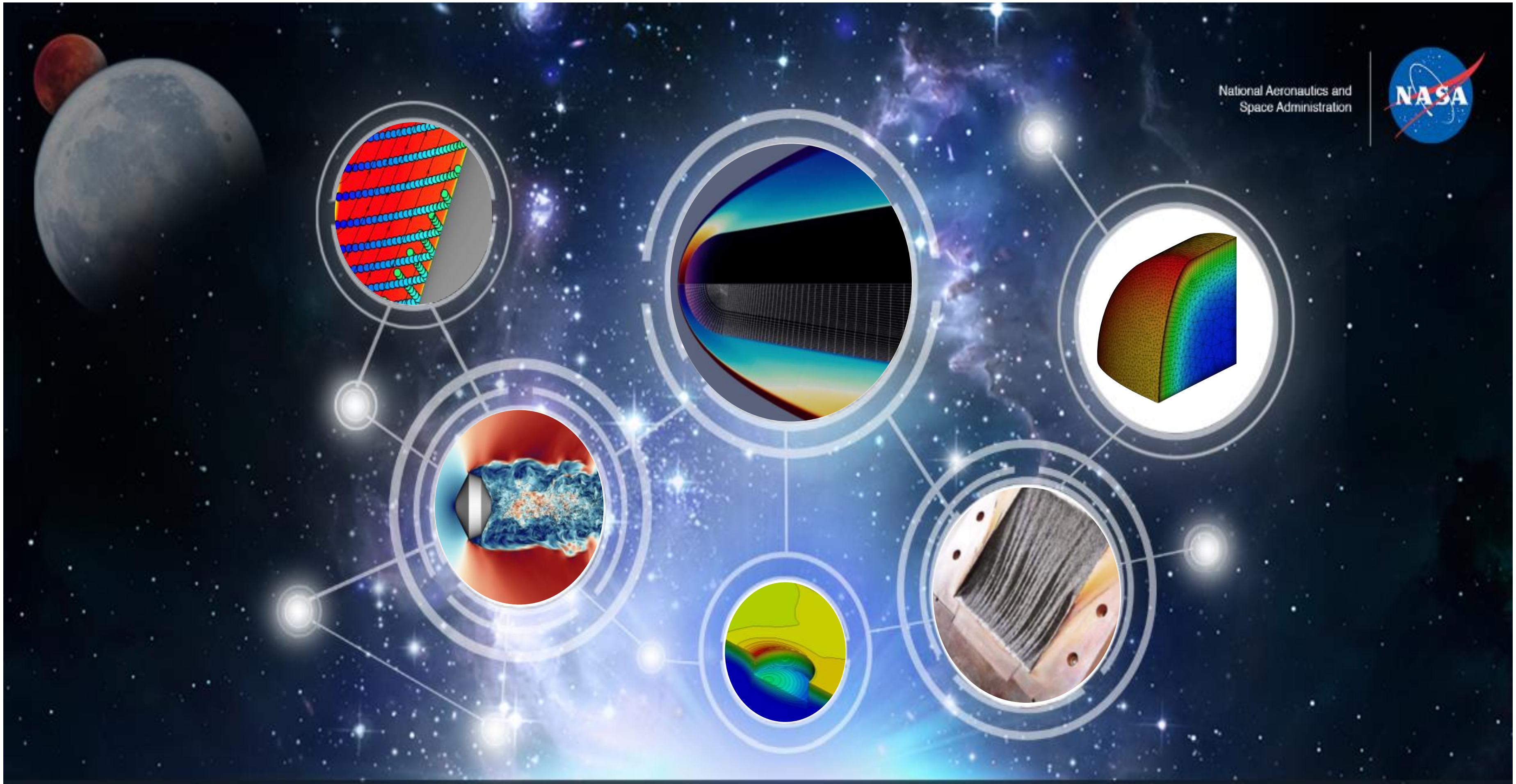

The Effect of Drag Model on Heatshield Recession due to Particle Impacts for Martian Spacecraft

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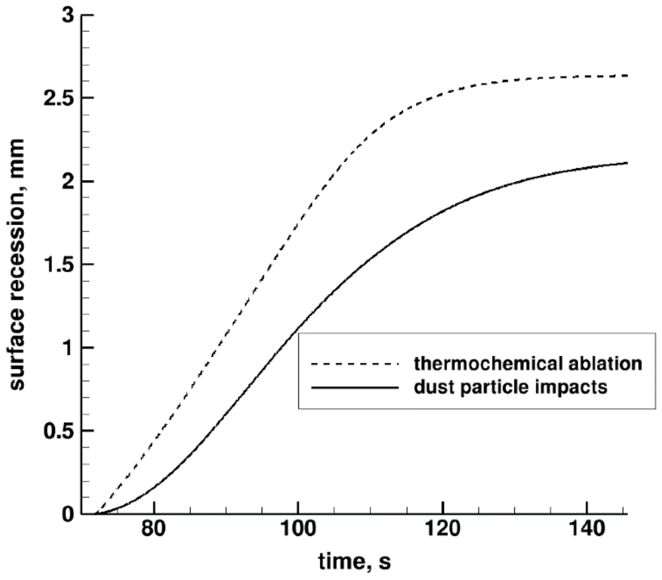
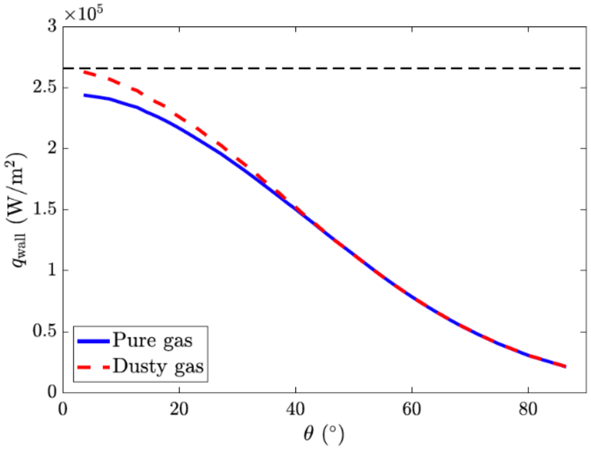
Background – Effects of Dusty Flow

- A spacecraft entering the Martian atmosphere may encounter a major regional or global dust storm.
- Effects of dust particles traveling through the shock layer include:
  - Heatshield erosion due to dust particle impacts.
  - Surface heating rate augmentation.
  - Changes to radiative heating.



Surface recession from particle impacts compared to recession from thermochemical ablation, Schiaparelli entry capsule.



Heating rate augmentation with dusty flow.

Characterizing Dusty Flow Conditions

- Dusty flow conditions can be characterized by the non-dimensional particle Reynolds, Mach, and Knudsen number.

Reynolds number $$Re = \frac{\rho_g \left|\Delta\vec{V}\right| d_p}{\mu_g}$$

Mach number $$M = \frac{\left|\Delta\vec{V}\right|}{c}$$

Knudsen number $$Kn = \sqrt{\frac{\pi\gamma}{2}}\left(\frac{M}{Re}\right)$$

- The particle non-dimensional numbers are similar to the standard definitions but are based on the relative velocity between the particles and surrounding fluid, $\Delta\vec{V}$.

Relative particle velocity: $$\Delta\vec{V} = \overrightarrow{v_g} - \overrightarrow{v_p}$$

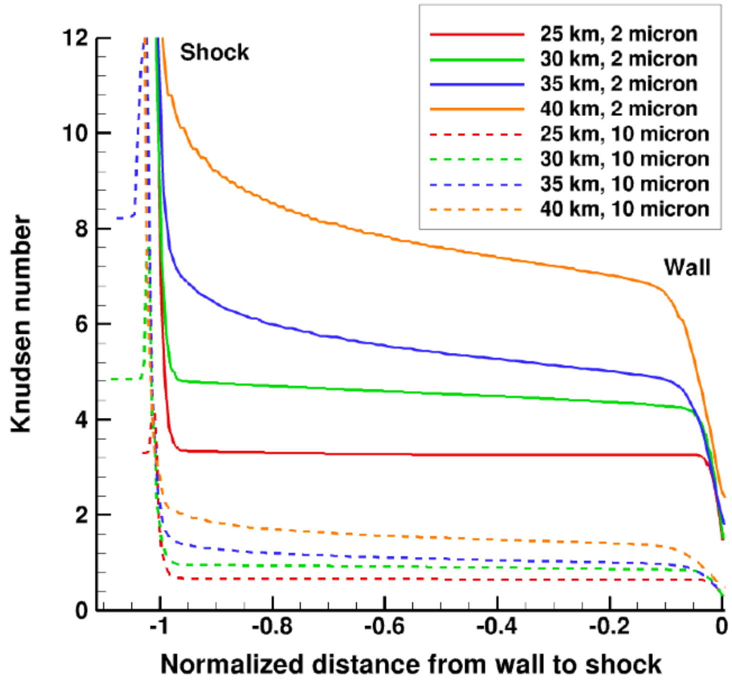
Particle Knudsen Number

- Particle Knudsen number is the ratio of the mean free path of the fluid surrounding the particle to the particle diameter. It defines the flow regime around the particle – from continuum to free-molecular flow.

Rarefaction regimes

Flow Regime	Kn
Continuum	< 0.01
Slip	0.01 – 0.1
Transitional	0.1 - 10
Free-molecular	> 10

Martian dust particles will be in the transitional flow regime



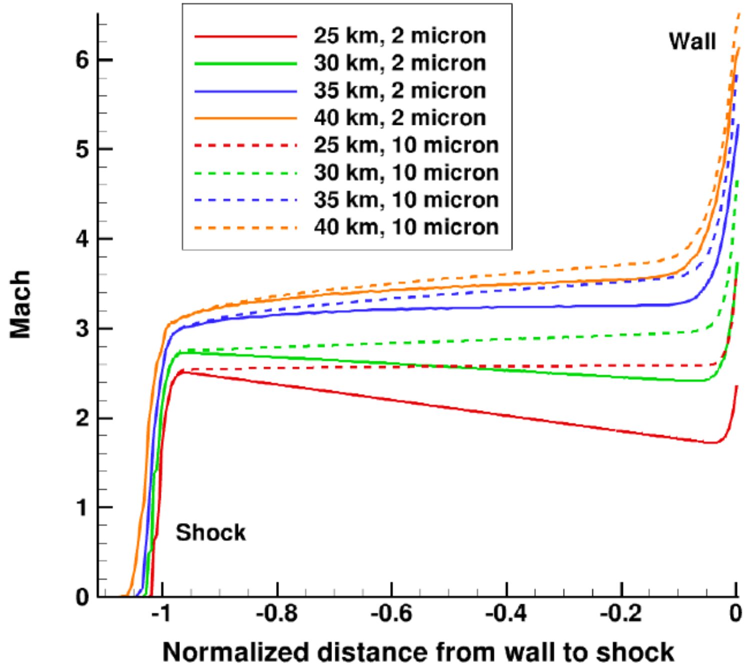
Particle Mach Numbers

- Particle Mach number defines the compressibility effects experienced by the particle – from incompressible to hypersonic flow.

Compressibility regimes

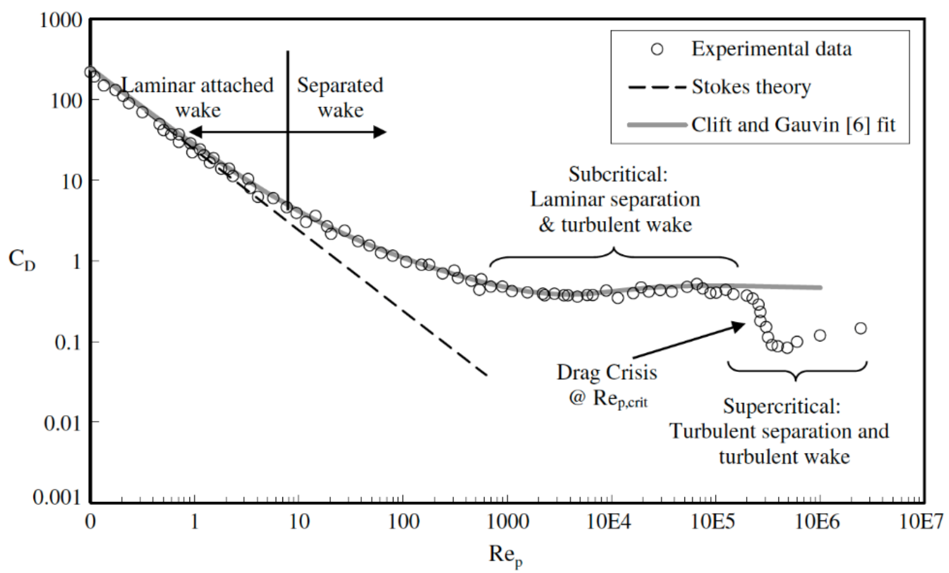
Flow Regime	*M*
Incompressible	< 0.1
Compressible, subsonic	0.1 – 0.65
Transonic	0.65 – 1.2
Supersonic	1.2 – 5
Hypersonic	> 5

Martian dust particles will be in the supersonic flow regime



Particle Reynolds Number

- Particle Reynolds number is the ratio of the inertial and viscous forces acting on the particle. It determines the nature of the flow around the particle and in the wake and has a strong influence on the drag force exerted on the particle.



Drag coefficient can vary by orders of magnitude based on Reynolds number.

Drag coefficient as a function of particle Reynolds number for incompressible, continuum flow, from Loth, et al [2021].

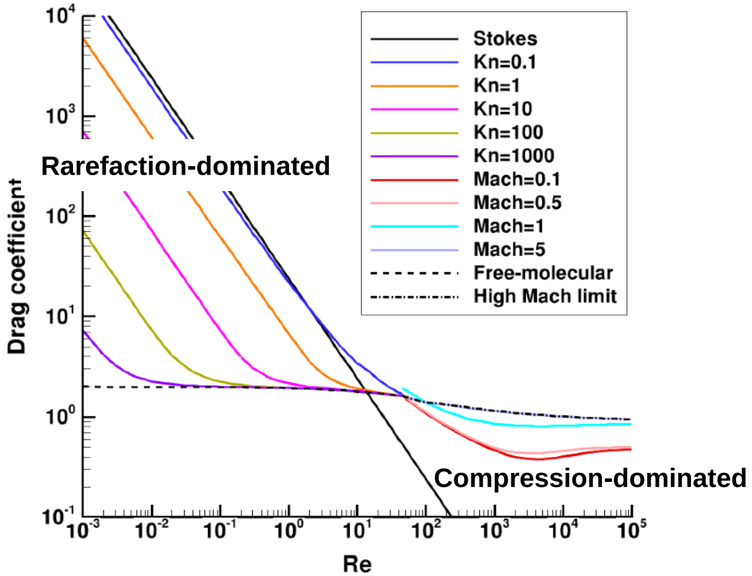
Particle Drag Regimes

- Particle trajectories are primarily influenced by the drag force on the particle.

$$\overrightarrow{F_D} = m_p \frac{d\overrightarrow{V_p}}{dt} = \frac{1}{2}\rho_g |\Delta \vec{V}| \Delta\vec{V} C_D A = \frac{1}{8}\pi d_p^2 \rho_g |\Delta \vec{V}| \Delta\vec{V} C_D$$

- Particle Reynolds number defines the drag regime experienced by the particle and the nature of the drag coefficient, C_D.
  - At Re ~ 45, the drag coefficient is relatively independent of Knudsen and Mach number.
  - For Re < 45, the particle is in the rarefaction-dominated drag regime. C_D primarily influenced by Knudsen number.
  - For Re > 45 , the particle is in the compression-dominated drag regime. C_D primarily influenced by Mach number

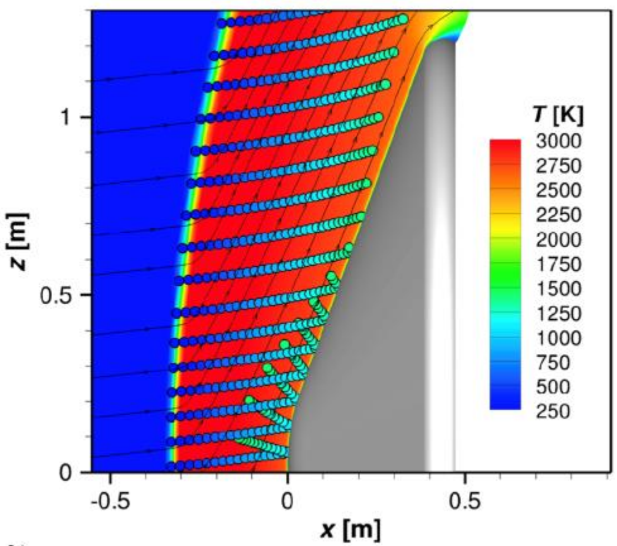
Reynolds numbers for Martian dust particles will be generally less than 10.



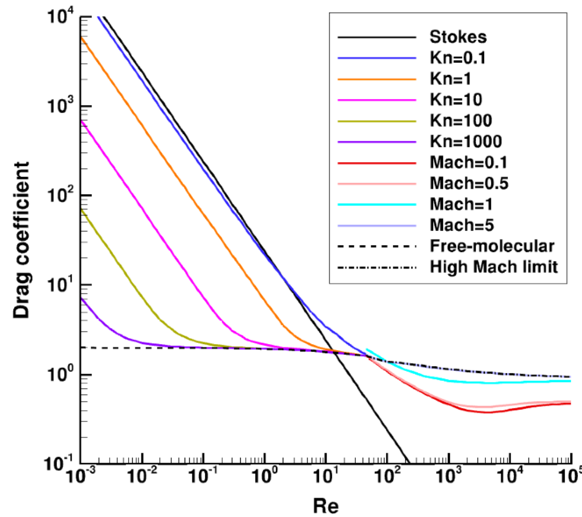
Particle drag coefficient as a function of Reynolds number (Loth particle drag model)

Flow Situation in Shock Layer

- When dust particles strike the bow shock of a Martian entry vehicle, the initial relative particle velocity is high.
- Drag force acting on the particle will slow the particle down as it travels through the shock layer towards the heatshield.
- In the rarefaction-dominated drag regime (Re < 45), including Knudsen number effects will decrease particle drag coefficient, and increase impact velocity.



Simulation of dust particles traveling through Martian shock layer



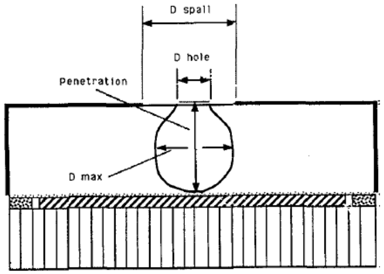
Particle drag coefficient as a function of Reynolds number (Loth particle drag model)

Surface Damage Models

- If they strike with sufficient energy, dust particles can cause spallation damage to the heatshield of Martian entry capsules.
- Research by Greely and Schulz [1974] determined that diameter of the impact crater, D_c, from a particle impact is roughly proportional to the cube root of the particle kinetic energy at impact.
- For spherical particles (a typical assumption), the cube root of particle kinetic energy is a function of the particle material density, ρ_p, particle diameter, d_p, and the impact velocity, v_p.

$$D_c \propto \rho_p^{0.33} d_p v_p^{0.667}$$

Idealized particle impact crater diameter



Schematic of particle impact crater

Particle Drag Models

- Researchers have been developing particle drag models for 170 years. Some of those models include:
  - Stokes (1851)
  - Schiller-Naumann (1933)
  - Clift-Gauvin (1970)
  - Henderson (1976)
  - Haider-Levenspiel (1989)
  - Loth (2008)
  - Loth, et al. (2021)
  - Singh, et al. (2021)

All of these drag models except Haider-Levenspiel assume spherical particles

- A lot of effort has been spent developing particle drag models for a wide range of conditions – but for the specific application of simulating heatshield erosion during a Martian entry how much difference do particle drag models make?

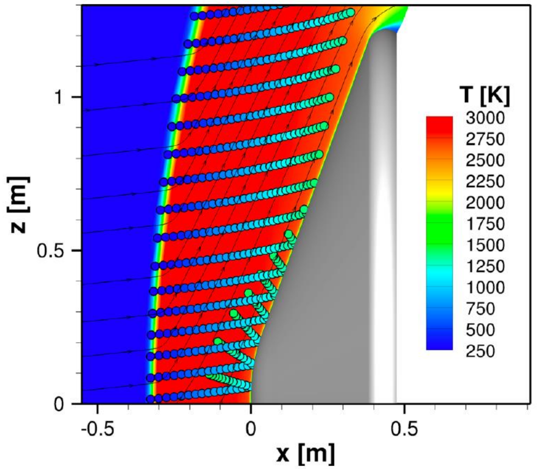
Particle Drag Models

- This paper examines three particle drag models – all are intended for spherical particles.
- Clift-Gauvin [1970]
  - Extends simple Stokes drag correlation to higher Reynolds numbers.
  - Intended for incompressible, continuum particle flow conditions.
- Henderson [1976].
  - Valid over a wide range of Reynolds, Knudsen, and Mach numbers.
  - Based primarily on ballistic range data in the continuum and slip flow regimes.
- Loth [2021]
  - Valid over a wide range of Reynolds, Knudsen, and Mach numbers.
  - Based on additional experimental and DSMC data in the slip and transitional regimes.
- Martian dust particles will experience compressible, supersonic, transitional flow conditions when traveling through the shock layer.

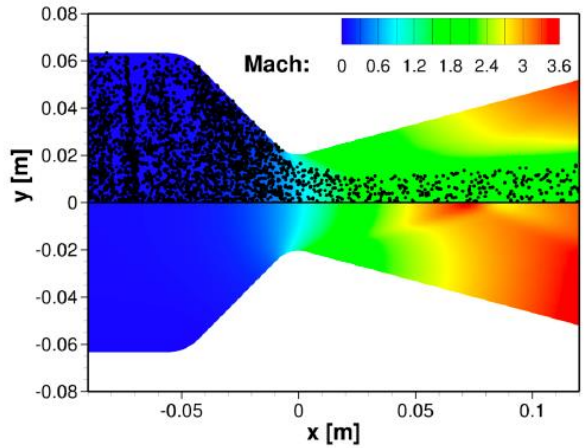
Integrated US3D-DUST Analysis Tool

- The integrated US3D-DUST code, developed under the NASA ESM project, is used to simulate Martian dusty flow environments.
- US3D – a 3-D unstructured Navier-Stokes flow solver developed at the University of Minnesota.
- The Dust Simulation and Tracking (DUST) code is a Lagrangian-based particle trajectory capability integrated into US3D as an external library.
  - US3D-DUST has been used to simulate dusty-flow experiments and particle trajectories through Martian shock layers.

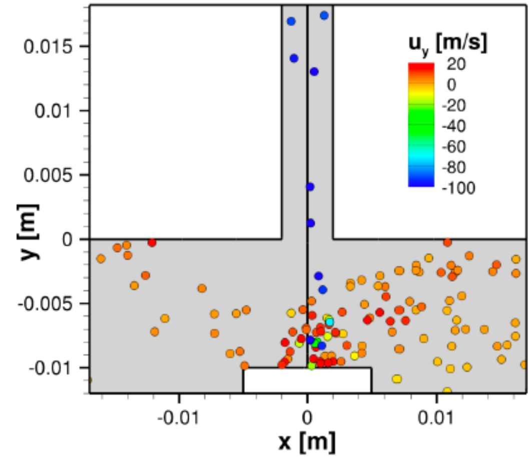
1-Way: Schiaparelli



2-Way: Caltech Nozzle



4-Way: Jet Impingement



Source: Sahai *et. al*, AIAAJ (2022)

Martian Dusty-Flow Conditions

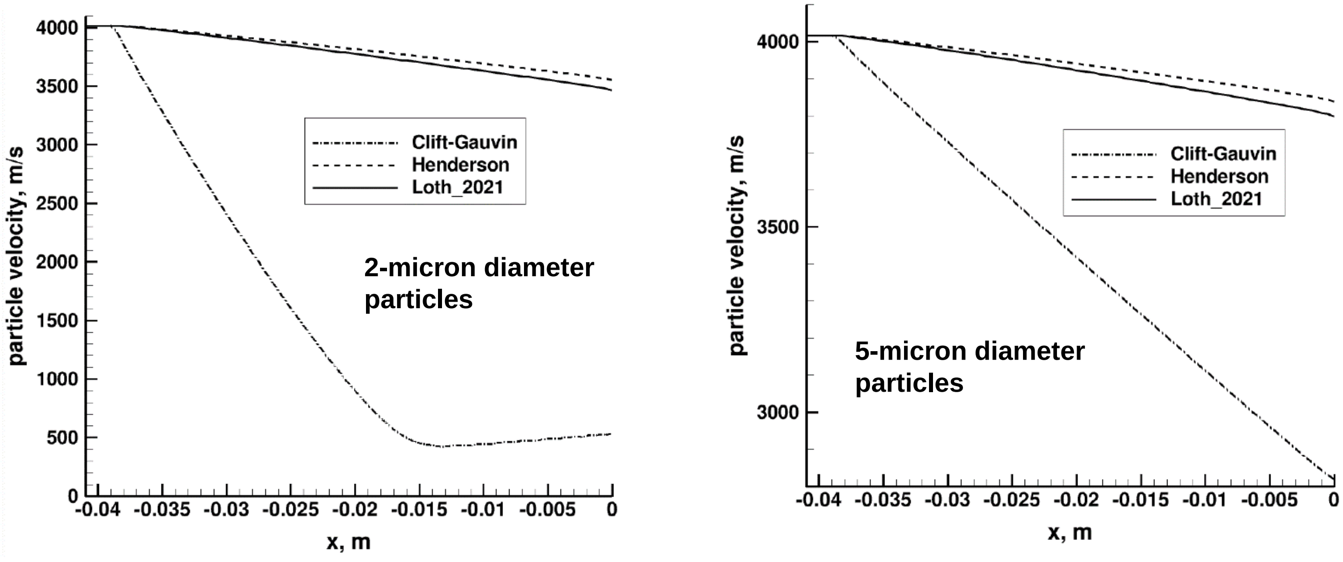
- US3D-DUST used to simulate particles traveling through a Martian shock layer at seven points along Schiaparelli capsule entry trajectory.
  - Dust conditions corresponded to 2007 major global dust storm.
  - Particle size distribution based on modified gamma distribution function with 0.41-micron mode radius.
  - Particle number densities based on dust opacity measurements taken by the Mars Climate Sounder.
  - US3D-DUST computes average surface recession rate at every surface grid face.

Schiaparelli capsule entry trajectory points

Time, s	Altitude, km	Density, kg/m^3	Velocity, m/s	Temperature, K	Angle of attack, deg
71.7	50.0	1.755e-4	5500.6	171.8	7.2
78.9	45.0	2.944e-4	5185.0	175.0	7.2
87.2	40.0	4.825e-4	4689.0	182.4	7.2
96.3	35.0	7.717e-4	4016.9	186.3	7.2
110.8	30.0	1.322e-3	2913.7	190.1	6.0
125.6	25.5	1.979e-3	2013.8	195.4	5.0
145.6	20.9	2.962e-3	1236.9	202.3	3.0

Results – Particle Velocities through Shock Layer

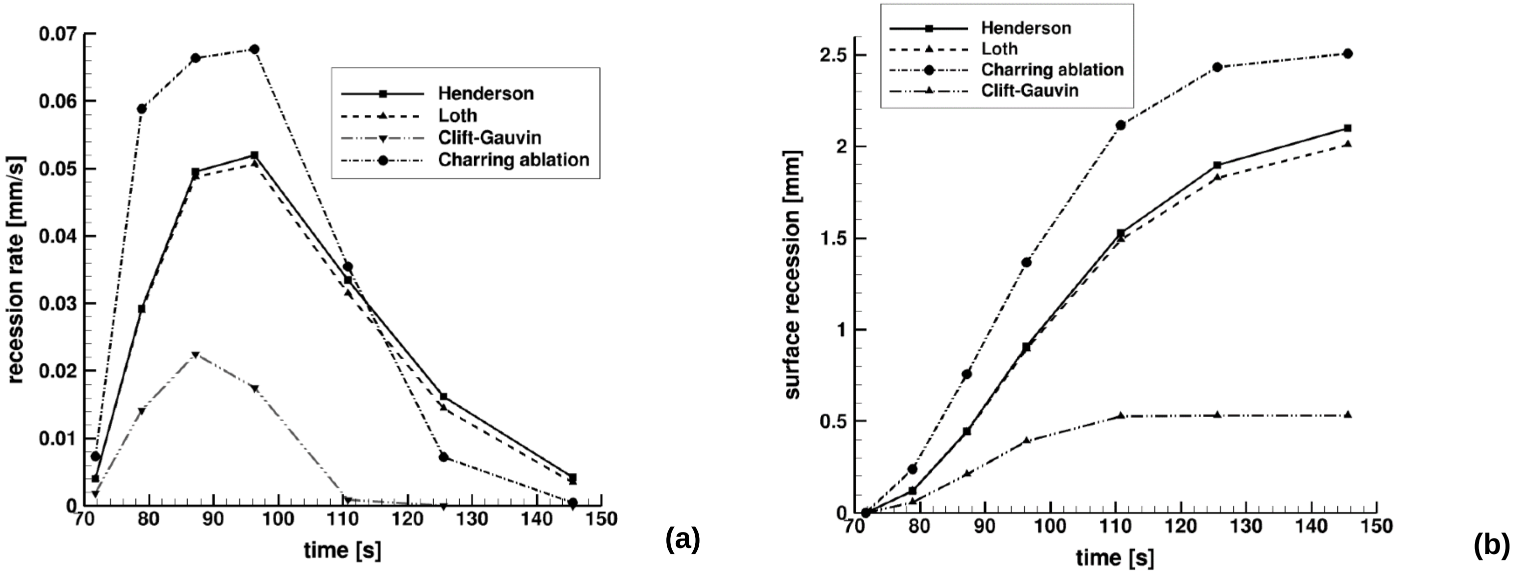
- Clift-Gauvin model assumes incompressible, continuum flow. Predicts much higher particle drag coefficient and deceleration in Martian shock layer compared to Henderson and Loth models.
- Loth and Henderson drag models yield similar results. Loth model predicts slightly higher drag coefficients and therefore lower particle velocities.
- The drag model applied to Martian entry problems must account for Knudsen and Mach number effects.



Particle velocities through shock layer along stagnation line.

Results – Predicted Heatshield Recession

- Clift-Gauvin drag model, that does not include Knudsen and Mach number effects, predicts much lower recession rate and cumulative recession values.
- Loth and Henderson drag models yield similar results. Loth model predicts slightly higher drag coefficients and therefore slightly lower recession.
  - The Loth and Henderson values are within the overall uncertainty of the particle trajectory, surface damage solution process.
- Surface recession due to dust particle impacts predicted by Henderson and Loth drag models comparable to predicted heatshield recession due to thermochemical ablation (i.e., charring)

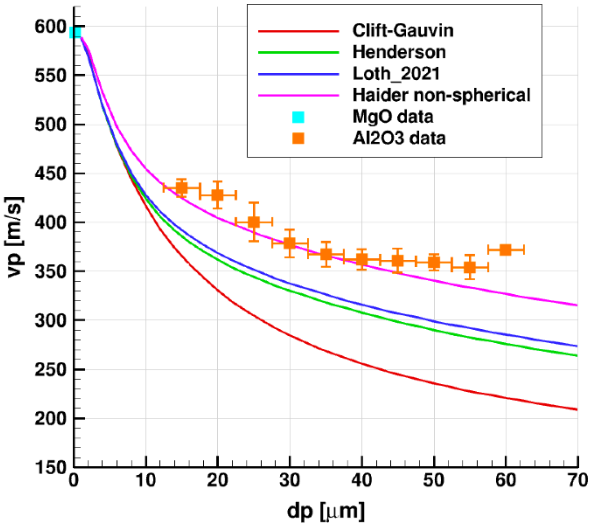


Effect of particle drag model on surface recession. (a) recession rate. (b) cumulative recession

Non-spherical Particle Effects

- All of the drag models discussed in this presentation assume spherical particles – but Martian dust particles are most likely non-spherical.
- It is well-known that non-spherical particles experience higher drag coefficients.
  - US3D-DUST simulations of DLR GBK experiments show that using the Haider-Levenspiel non-spherical drag model is needed to match experimental measurements of Al_2O_3 particle velocity at the nozzle exit plane.
- In Martian shock layers, accounting for non-spherical effects would increase particle drag force and decrease impact velocity and surface damage. Assuming spherical particles is a conservative analysis approach.

Measured particle velocity downstream of nozzle exit plane, DLR GBK facility



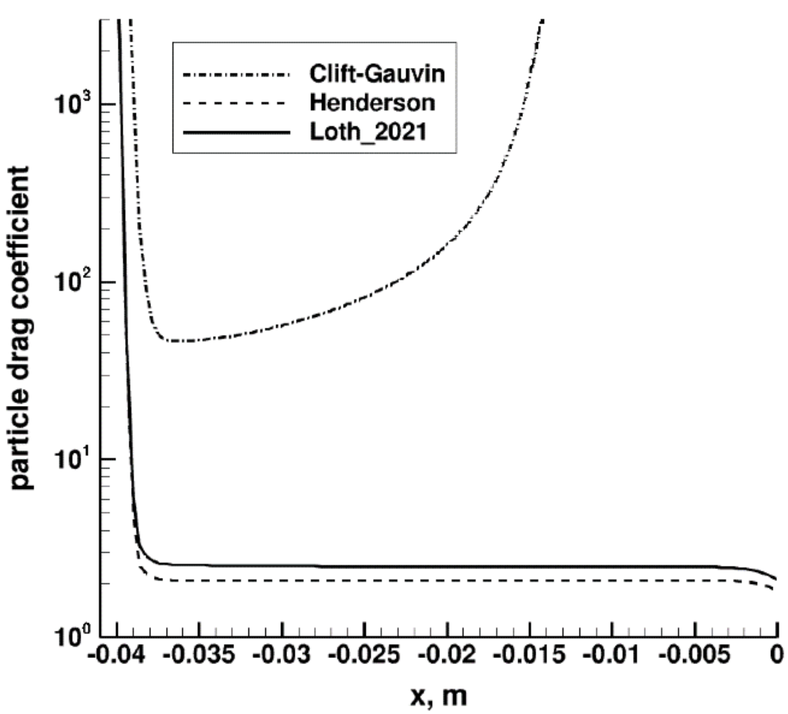
Concluding Remarks

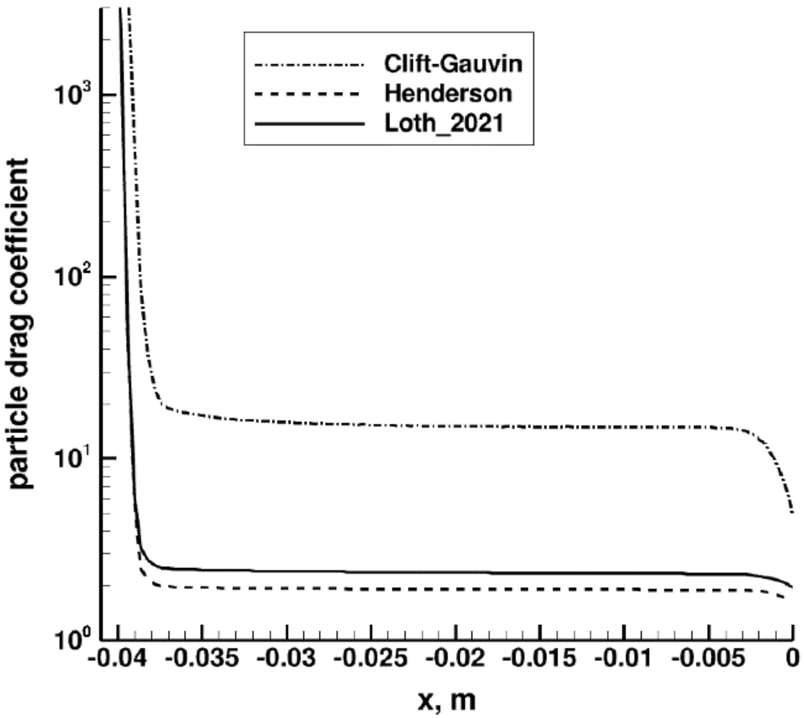
- The US3D-DUST code was used to simulate dusty-flow conditions in Martian shock layers to determine whether and to what extent the choice of particle drag model affects predicted surface recession rates and cumulative recession due to dust particle impacts.
- A drag model that does not account for Knudsen and Mach number effects, such as the Clift-Gauvin model, will predict much higher particle drag coefficient compared to the Henderson and Loth models.
- Surface recession predicted by the Henderson and Loth drag models, which are applicable over a wide range of particle flow conditions, are similar and within the overall uncertainty of the solution process.
- Including non-spherical particle effects increases drag coefficients and decreases impact velocity and surface damage – a conservative analysis approach is to assume spherical particles.

Backup Slides

- Backup Slides

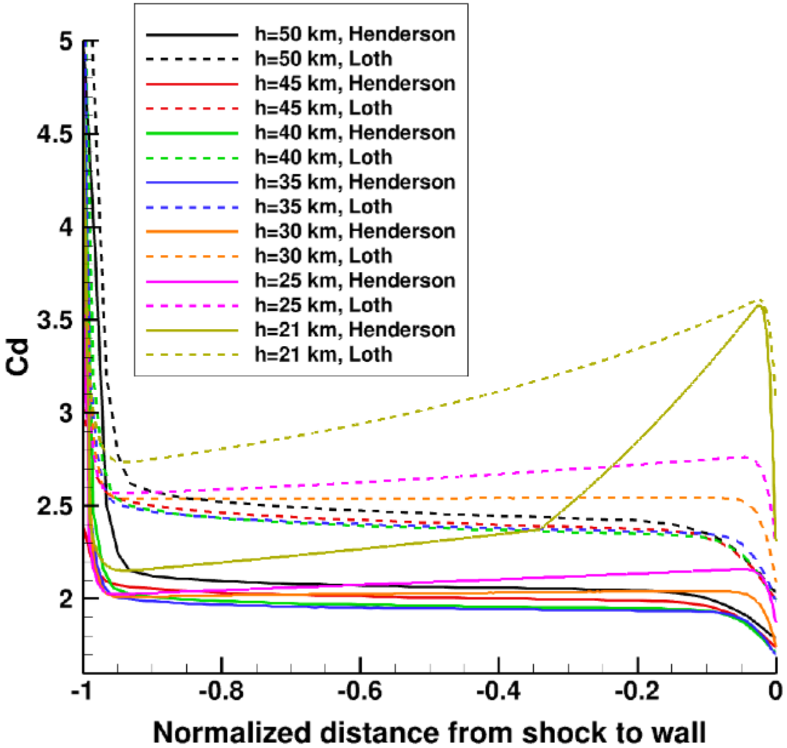
Drag Coefficient in Martian Shock Layer

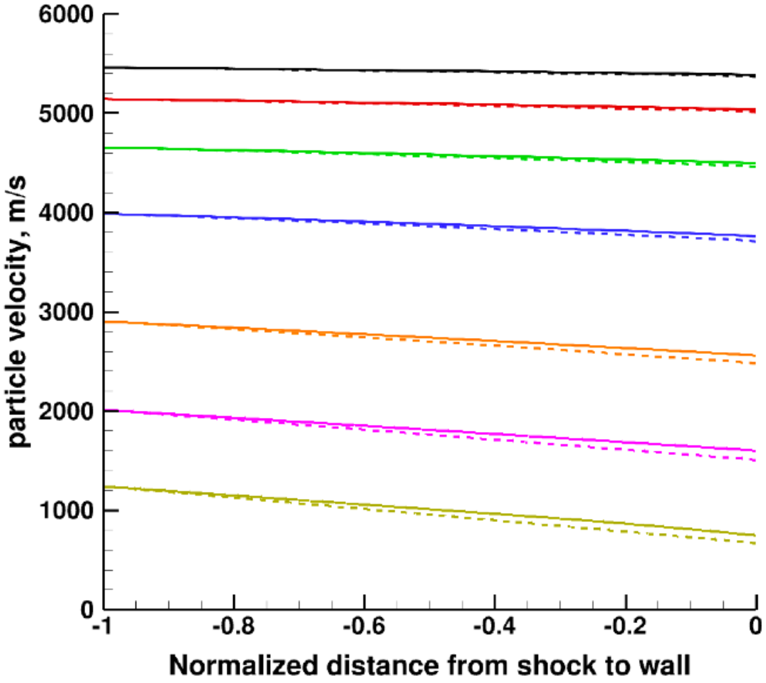




Drag coefficient profiles of particles traveling through the 35km altitude shock layer. (a) 2-micron diameter particles. (b) 5-micron diameter particles

Drag Coefficient in Martian Shock Layer





Shock layer profiles for 4-micron particles at different Schiaparelli trajectory points. (a) drag coefficient. (b) particle velocity

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